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(54) Carburizing and carbonitriding steel

(57) A carburizing and carbonitriding steel, comprising, in percent by weight, C = 0.10 to 0.30%, Si = 0.40 to 1.00%, Mn = 0.30 to 1.50%, P = 0.035% or lower, S = 0.005 to 0.050%, Ni = 0.00 to 1.00%, Cr = 0.30 to 1.50%, Cu = 0.01 to 0.50%, Mo = 0.00 to 1.00%, Al = 0.010 to 0.035%, Nb = 0.001 to 0.050%, N = 0.0050 to 0.0200%, and O = 0.0015% or lower, wherein the parameter expressed as Mo + Ni ranges from 0.30% to 2.00%, with the balance being Fe and unavoidable impurity elements. The steel further contains one or more elements of V = 0.01 to 0.50%, Ti = 0.005 to 0.050%, and B = 0.0005 to 0.0050%. As elements that improve machinability without severely affecting fatigue characteristics, the steel may further contain one or more elements of Pb = 0.01 to 0.09%, Bi = 0.04 to 0.20%, Te = 0.002 to 0.050%, Zr = 0.01 to 0.20%, Ca = 0.0001 to 0.0100%. The steel is improved in pitting fatigue strength and impact strength at the same time because of the need to reduce the size and weight of mechanical components and to achieve higher stress load levels.

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Description

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates to a steel to be subjected to carburizing and carbonitriding for the use in gears and shafts, which are required to have high pitting fatigue strength and high impact strength.

2. Description of the Related Art

[0002] Examples of conventional techniques aimed at reducing the grain-boundary oxide phases, which may cause fatigue cracks, in order to achieve higher flexural fatigue strength include those that entail reducing the content of elements more readily oxidizable than Fe (such as Si, Mn, and Cr) and adjusting hardenability and mechanical properties by means of elements less readily oxidizable than Fe (such as Ni and Mo); and those that entail obtaining surface-compression residual stress by employing shot peening to delay the spreading of fatigue cracks. According to some reports, adding Si or V in order to improve pitting fatigue strength has been studied as a promising means because of its ability to improve flexural fatigue strength.
[0003] Gears and shafts that are more compact and lightweight and are capable of withstanding higher levels of stress loading are currently needed in order to be able to reduce the weight and to increase the engine output of automobiles and industrial machinery. Improved pitting fatigue strength and impact strength are needed as a result. With the conventional techniques, however, it is difficult to achieve both goals at the same time.

SUMMARY OF THE INVENTION

[0004] In view of these drawbacks, it is an object of the present invention to simultaneously improve pitting fatigue strength and impact strength merely by adjusting the chemical composition of steel.
[0005] The means for attaining the stated object resides in improving the temper hardness of the carburized or carbonitrided steel by increasing the Si content thereof, and in improving the fracture toughness of the carburized layer and the core by adding Ni and Mo either singly or in combination thereof.
[0006] Specifically, according to a first feature of the present invention, there is provided a carburizing and carbonitriding steel, comprising, in percent by weight,

C = 0.10 to 0.30%,

Si = 0.40 to 1.00%,

Mn = 0.30 to 1.50%,

P = 0.035% or lower,

S = 0.005 to 0.050%,

Ni = 0.00 to 1.00%,

Cr = 0.30 to 1.50%,

Cu = 0.01 to 0.50%,

Mo = 0.00 to 1.00%,

Al = 0.010 to 0.035%,

Nb = 0.001 to 0.050%,

N = 0.0050 to 0.0200%, and

O = 0.0015% or lower,

wherein the parameter expressed as Mo + Ni ranges from 0.30% to 2.00%, with the balance being Fe and unavoidable impurity elements.

[0007] In a second feature of the present invention, the above-specified carburizing and carbonitriding steel further contains, in percent by weight, at least one element selected from the group consisting of

V = 0.01 to 0.50%,

Ti = 0.005 to 0.050%, and

B = 0.0005 to 0.0050%.

[0008] In a third feature of the present invention, the carburizing and carbonitriding steel specified in the above first or second feature further contains, in percent by weight, at least one element selected from the group consisting of the following elements that improve the machinability of the steels without severely affecting the fatigue characteristics thereof:

Pb = 0.01 to 0.09%,

Bi = 0.04 to 0.20%,

Te = 0.002 to 0.050%,

Zr = 0.01 to 0.20%, and

Ca = 0.0001 to 0.0100%.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009]

Fig. 1 is a diagram depicting the shape of the test piece used for evaluating temper hardness;
Fig. 2 is a diagram depicting the shape of the test piece used for evaluating carburization impact strength;
Fig. 3 is a diagram illustrating the treatment conditions of carburizing, quenching, and tempering;
Fig. 4 is a graph depicting the relation between temper hardness and Si content;
Fig. 5 is a graph depicting the relation between carburization impact strength and Si content;

Fig. 6 is a graph depicting the relation between carburization impact strength and temper hardness;
Fig. 7 is a schematic of a roller/pitting fatigue tester;
Fig. 8 is a diagram depicting the shape of the roller/pitting fatigue tes[illegible]e;
Fig. 9 is a diagram depicting the shape of a loading roller for the roll[illegible]ng fatigue tester; and
Fig. 10 is a diagram depicting the relation between pitting fatigue life [illegible]carburization impact strength.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0010] As a result of painstaking research into pitting fatigue strength and impact strength, the inventors discovered a method in which strength can be improved in the generally possible chemical compositional range as carburizing and carbonitriding steels by adjusting their chemical composition.

[0011] The primary goal of adjusting these chemical components is to improve temper hardness by increasing the Si content and to improve the fracture toughness of the carburized layer and the core by adding Ni and Mo either singly or in combination thereof.

[0012] Extensive research involving numerous experiments had been conducted before this discovery was made. An example is shown below. According to past research, temper hardness and carburization impact strength are the most important factors that govern the pitting fatigue and impact strength of carburized gears. Table 1 shows the chemical compositions of inventive and comparative steels used to evaluate these factors.

Table 1

No.	Chemical Composition (wt %)																					Ni + Mo wt%)	Temper Hardness (HV)	Carburization impact strength (J/cm²)
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	Al	Nb	O	N	V	Ti	B	Pb	Bi	Te	Zr	Ca			
No. 1	0.30	0.40	0.68	0.007	0.050	0.00	0.30	0.08	0.30	0.025	0.022	0.0009	0.0050		-	-	-	-	-	-	-	0.30	712	28.8
No. 2	0.10	0.41	1.50	0.012	0.005	0.35	0.89	0.12	0.30	0.023	0.025	0.0010	0.0124	-	-	-	-	-	-	-	-	0.65	705	32.2
No. 3	0.21	0.68	0.55	0.011	0.014	0.00	0.75	0.01	0.65	0.024	0.020	0.0011	0.0178	-	-	-	-	-	-	-	-	0.65	721	31.2
No. 4	0.20	1.00	0.30	0.011	0.012	0.65	1.50	0.36	0.00	0.023	0.021	0.0007	0.0133	-	-	-	-	-	-	-	-	0.65	720	28.8
No. 5	0.20	0.45	0.43	0.020	0.012	1.00	0.55	0.22	0.00	0.010	0.050	0.0015	0.0145	-	-	-	-	-	-	-	-	1.00	708	33.6
No. 6	0.21	0.70	0.44	0.018	0.013	0.00	0.44	0.05	1.00	0.050	0.001	0.0012	0.0200	-	-	-	-	-	-	-	-	1.00	712	32.6
No. 7	0.17	0.76	0.37	0.035	0.025	1.00	0.40	0.08	0.50	0.018	0.021	0.0008	0.0138	-	-	-	-	-	-	-	-	1.50	712	35.3
No. 8	0.12	0.98	0.32	0.021	0.035	1.00	0.34	0.50	1.00	0.027	0.024	0.0011	0.0108	-	-	-	-	-	-	-	-	2.00	709	37.8
No. 9	0.20	0.97	0.33	0.015	0.035	0.49	0.39	0.23	0.51	0.024	0.003	0.0009	0.0138	0.50	-	-	-	-	-	-	-	1.00	715	31.0
No.10	0.20	0.72	0.73	0.016	0.011	0.14	0.88	0.10	0.16	0.033	0.001	0.0009	0.0050	0.01	0.005	0.0005	-	-	-	-	-	0.30	723	27.4
No.11	0.10	0.99	1.50	0.013	0.014	0.30	1.50	0.22	0.00	0.035	0.002	0.0010	0.0089	-	0.050	0.0050	-	-	-	-	-	0.30	717	26.2
No.12	0.22	0.43	0.68	0.012	0.015	0.02	1.05	0.05	0.28	0.025	0.001	0.0007	0.0178	-	-	-	0.09	0.04	-	-	-	0.30	717	28.5
No.13	0.21	0.40	0.65	0.015	0.016	0.45	0.77	0.29	0.55	0.023	0.004	0.0009	0.0144	-	-	-	0.01	0.20	0.002	-	-	1.00	707	34.2
No.14	0.22	0.74	0.71	0.012	0.010	0.35	0.86	0.09	0.30	0.024	0.003	0.0010	0.0193		-	-	-	-	0.050	0.01	-	0.65	715	30.4
No.15	0.20	0.95	0.46	0.010	0.013	0.28	0.82	0.11	0.02	0.027	0.001	0.0010	0.0099	-	-	-	-	-	-	0.20	0.0001	0.30	726	26.0
No.16	0.22	1.00	0.45	0.014	0.014	0.52	0.76	0.36	0.48	0.024	0.002	0.0011	0.0125	-	-	-	-	-	-	-	0.0100	1.00	726	30.5
A	0.22	0.18	0.75	0.015	0.012	0.02	1.05	0.10	0.22	0.025	-	0.0011	0.0099	-	-	-	-	-	-	-	-	0.24	671	30.3
B	0.21	0.42	0.62	0.014	0.012	0.02	1.05	0.10	0.15	0.025	-	0.0011	0.0099	-	-	-	-	-	-	-	-	0.17	703	17.0
C	0.19	0.72	0.51	0.012	0.011	0.02	1.05	0.11	0.10	0.021	-	0.0009	0.0188	-	-	-	-	-	-	-	-	0.12	704	8.5
D	0.21	0.99	0.50	0.015	0.014	0.02	0.97	0.09	0.02	0.028	-	0.0008	0.0123	-	-	-	-	-	-	-	-	0.04	707	6.0
E	0.21	0.23	0.45	0.015	0.010	0.02	0.90	0.09	0.28	0.028	-	0.0008	0.0156	-	-	-	-	-	-	-	-	0.30	688	30.1
F	0.21	0.08	0.40	0.015	0.010	0.27	0.86	0.09	0.38	0.028	-	0.0008	0.0156	-	-	-	-	-	-	-	-	0.65	675	32.7
G	0.22	0.12	0.41	0.014	0.013	0.68	0.89	0.11	0.32	0.021	-	0.0015	0.0151	-	-	-	-	-	-	-	-	1.00	666	35.3

Nos. 1-8: first inventive steels, Nos. 9-11: second inventive steels
Nos. 12-16: third inventive steels, Nos. A-G: comparative steels

[0013] In the table, "first inventive steel", "second inventive steel" and "third inventive steel" correspond to the above-

prescribed first feature, second feature and third feature, respectively, of the present invention. These types of steel were melted in a highfrequency vacuum melting furnace. The ingots thus obtained were heated to 1250°C, cogged to a diameter of 30 mm, and normalized at 925°C. The blanks were machined, yielding a single test piece, having a shape shown in Fig. 1, for evaluating temper hardness and three test pieces, shaped as shown in Fig. 2, for evaluating impact strength. All these test pieces were carburized, quenched, and tempered under the conditions shown in Fig. 3.

[0014] The test piece for determining temper hardness shown in Fig. 1 was air-cooled after being kept for 8 hours in an electric furnace heated at 250°C under conditions simulating those under which frictional heat is generated during the rolling of a gear. The air-cooled test pieces were cut perpendicular to the longitudinal direction, hardness was measured every 10 μm with a Microvickers hardness meter up to a depth of 50 μm from the surface at two arbitrary locations (at 90° intervals), and the results were averaged. These results are shown in Table 1 above as post-temper hardness values. The three test pieces, shown in Fig. 2, for each of different steels for determining carburizing impact were subjected to Charpy impact tests, and average Charpy impact values were calculated. These results are shown in Table 1 above as carburization impact strength values. The data are described in detail below.

[0015] Fig. 4 shows the relation between temper hardness and Si content. It can be seen in the drawing that when the Si content is 0.40 wt% or higher, the temper hardness is 700 HV or greater, which is higher than the temper hardness of a steel product having an Si content lower than 0.40 wt%. This is because surface hardness can be kept at a high level (even after tempering has been performed under conditions simulating those created when frictional heat is generated during the rolling of a gear) by increasing the Si content, which enhances tempering/softening resistance as previously indicated. Fig. 5 shows the relation between carburization impact strength and Si content. It can be seen that when the combined content of Ni and Mo is less than 0.30 wt%, carburization impact strength decreases with increase in the Si content. This is attributed to the fact that the fracture toughness of the carburized layer and the core decreases due to increased Si content. It can also be seen that even when the combined content of Ni and Mo is 0.30 wt% or more, carburization impact strength decreases slightly with increased Si content, but the rate of this increase is much lower than that observed when the combined content of Ni and Mo is less than 0.30 wt%. This is attributed to the fact that the fracture toughness of the carburized layer and the core can be kept at a high level by adding Ni or Mo despite increased Si content. It can thus be seen that high temper hardness and carburization impact strength can be obtained within the range of the present invention, where the Si content is 0.40 wt% or higher and the Ni + Mo parameter, which is equal to the combined content of Ni and Mo, is 0.30 wt% or higher.

[0016] The above-described relationships are illustrated in Fig. 6, which depicts the relation between temper hardness and carburization impact strength. It can be seen that the inventive steel is much more beneficial than a comparative steel, for achieving higher temper hardness and carburization impact strength.

[0017] The present invention is based on the above-described research results. Described below are the reasons for setting limits to the chemical composition of the present invention. The chemical composition of gear steel is adjusted in a variety of ways with consideration for the factors related to the operating environment, such as gear size, load strength, and carburizing or carbonitriding conditions. It has been confirmed that the present invention provides the above effects in all possible ranges of chemical compositions, and the following compositional ranges are provided.

C: 0.10 to 0.30 wt%

[0018] At least 0.10 wt% C must be added in order to provide a gear with the required core strength. An excessive addition. however, makes the core unnecessarily hard and adversely affects core toughness. To prevent this, the upper limit must be set to 0.30 wt%.

[0019] Consequently, the C addition is confined to a range of 0.10 to 0.30 wt%.

Si: 0.40 to 1.00 wt%

[0020] Si is the most important element of the inventive steel. Specifically, Si is an element that reduces softening within a temperature range of 200 to 250°C, which a gear or the like is believed to reach during rolling. To achieve this effect, at least 0.40 wt% must be added. An excessive addition, however, adversely affects not only the toughness of the carburized layer and the core, but also the cold-forging properties or machinability due to inhibited carburization or the excessively high hardness of uncarburized steel materials. To prevent this, the upper limit must be set to 1.00 wt%.

[0021] Consequently, the Si addition is confined to a range of 0.40 to 1.00 wt%.

Mn: 0.30 to 1.50 wt%

[0022] Mn is an element needed to maintain the desired hardenability, and it must be added in an amount of at least 0.30 wt%. An excessive addition, however, has an adverse effect on the cold-forging properties or machinability due to the excessively high hardness of uncarburized steel materials. To prevent this, the upper limit must be set to 1.50 wt%.

[0023] Consequently, the Mn addition is confined to a range of 0.30 to 1.50 wt%.

P: 0.035 wt% or lower

[0024] P is an element that lowers toughness or fatigue strength by segregating along austenite grain boundaries and embrittling the grain boundaries. The damage becomes pronounced at a content of greater than 0.035 wt%.

[0025] Consequently, the P content is set to 0.035 wt% or lower.

Ni: 0.00 to 1.00 wt%

[0026] Together with Mo (described below), Ni is the next most important element of the inventive steel after Si. Specifically, Ni is an element that improves the fracture toughness of the carburized layer and the core in the same manner as Mo does.

[0027] Consequently, this element must be added in the absence of an Mo addition. Ni is an expensive element, however, so adding too much of it is undesirable from the economic standpoint, and such an addition reduces surface hardness by promoting the formation of residual austenite, and has an adverse effect on cold-forging properties or machinability due to the excessively high hardness of uncarburized steel materials. To prevent this, the upper limit must be set to 1.00 wt%.

[0028] Consequently, the Ni addition is confined to a range of 0.00 to 1.00 wt%.

Cr: 0.30 to 1.50 wt%

[0029] Cr is an element needed to ensure desired hardenability, and it must be added in an amount of at least 0.30 wt%. An excessive addition, however, has an adverse effect on the cold-forging properties or machinability due to the excessively high hardness of uncarburized steel materials. To prevent this, the upper limit must be set to 1.50 wt%.

[0030] Consequently, the Cr addition is confined to a range of 0.30 to 1.50 wt%.

Mo: 0.00 to 1.00 wt%

[0031] Together with Ni (described above), Mo is the next most important element of the inventive steel after Si. Specifically, Mo is an element that improves the fracture toughness of the carburized layer and the core in the same manner as Ni does. Consequently, this element must be added in the absence of an Ni addition. Mo is an expensive element, however, so adding too much of it is undesirable from the economic standpoint, and such an addition has an adverse effect on cold-forging properties or machihability due to the excessively high hardness of uncarburized steel materials. To prevent this, the upper limit must be set to 1.00 wt%. Occasionally, the need to add this element may be dispensed with if Ni has been added in the manner described above.

[0032] Consequently, the Mo addition is confined to a range of 0.00 to 1.00 wt%.

Al: 0.010 to 0.035 wt%

[0033] Al is an element that combines with N to form AlN and acts to refine the size of austenite crystal grains, contributing through this grain-size refinement to improved toughness for the carburized layer and the core. At least 0.010 wt% of the element must be added to achieve this effect. An excessive addition, however, promotes the formation of Al_2O_3 inclusions, which have an adverse effect on the fatigue strength. To prevent this, the upper limit must be set to 0.035 wt%.

[0034] Consequently, the Al addition is confined to a range of 0.010 to 0.035 wt%.

Nb: 0.001 to 0.050 wt%

[0035] Nb is an element that binds with the C and N in the steel to form carbonitrides, and is effective for reducing the size of austenite crystal grains in the same manner as AlN is. Through this grain-size refinement, the element improves the toughness of the carburized layer and the core. Addition of the element in an amount of at least 0.01% is needed in order to obtain such effects. However, an excessive addition forms coarse carbonitrides, causes precipitation, and adversely affects the toughness of the carburized layer. To prevent this, the upper limit must be set to 0.050 wt%.

[0036] Consequently, the Nb addition is confined to a range of 0.001 to 0.050 wt%.

O: 0.0015 wt% or lower

[0037] O is an element that is present in the steel as oxide-based inclusions and that has an adverse effect on the fatigue strength.

[0038] Consequently, the upper limit for O is set to 0.0015 wt% or lower.

N: 0.0050 to 0.0200 wt%

[0039] N is an element that combines with Al and Nb to form AlN and NbN and acts to reduce the size of austenite crystal grains, contributing through this gain-size refinement to improved toughness for the carburized layer and the core. At least 0.0050 wt% of the element is needed to achieve this effect. An excessive addition causes foaming on the surface of the steel ingot during solidification and has an adverse effect on the forgeability of steel materials. To prevent this, the upper limit must be set to 0.0200 wt%.

[0040] Consequently, the N addition is confined to a range of 0.0050 to 0.0200 wt%.

Parameter expressed as Ni + Mo: 0.30 wt% to 2.00%

[0041] As noted in the corresponding sections, Ni and Mo are elements designed to improve the fracture toughness of the carburized layer or the core whose fracture toughness has been reduced by increased Si addition. The parameter expressed as Ni + Mo must be added in an amount of at least 0.30 wt%. Ni and Mo are expensive, however, so adding too much of them is undesirable from the economic standpoint, and such an excessive addition deteriorates the cold-forging properties or machinability due to the excessively high hardness of uncarburized steel materials. To prevent this, the upper limit of the combined amount of these elements must be set to 2.00 wt%.

Cu: 0.01 to 0.50 wt%

[0042] Cu is an element that can be expected to have a precipitation hardening effect at comparatively high temper-

atures (400 to 600°C). It should therefore be added when rigorous operation conditions are anticipated (such as those resulting from a marked increase in the temperature of a gear or a rolling surface) or when there is a possibility that a high-temperature environment will be created near a jet engine or a turbine, as in an aircraft material. In order to exhibit this effect, addition of at least 0.01% of Cu is needed. However, an excessive addition promotes hot embrittlement and impairs carburization. To prevent this, the upper limit must be set to 0.50 wt%.

[0043] Consequently, the Cu addition is confined to a range of 0.01 to 0.50 wt%.

V: 0.01 to 0.50 wt%

[0044] V is an element that forms carbides even at comparatively low temperatures (near the carburization temperature), and is thus expected to improve hardness and hardenability at the same time. The element should therefore be added in an amount of at least 0.01% in order to obtain such effects. However, an excessive addition has an adverse effect on the toughness of the carburized layer and is undesirable from the economic standpoint because V is an expensive element. Such an excessive addition also has an adverse effect on cold-forging properties or machinability due to the excessively high hardness of uncarburized steel materials. To prevent this, the upper limit must be set to 0.50 wt%.

[0045] Consequently, the V addition is confined to a range of 0.01 to 0.50 wt%.

Ti: 0.005 to 0.050 wt%

[0046] Ti is an element added to prevent situations in which the N in the steel binds with B (described below), forming BN and reducing the hardenability improvement effect of B. At least 0.005% addition of the element is therefore needed in order to obtain such an effect. However, adding a large amount may produce coarse TiN, which serves as a starting point for fatigue fracturing. It is therefore necessary to set the upper limit to 0.050 wt%.

[0047] Consequently, the Ti addition is confined to a range of 0.005 to 0.050 wt%.

B: 0.0005 to 0.0050 wt%

[0048] B is an element that improves the hardenability without adversely affecting the cold-forging properties or machinability of uncarburized steel materials. Addition of the element in an amount of not less than 0.0005 wt% is therefore needed in order to exhibit this effect. However, even when more than 0.0050 wt% is added, the effect reaches saturation and results in reduced hot workability. It is therefore necessary to set the upper limit to 0.0050 wt%.

[0049] Consequently, the B addition is confined to a range of 0.0005 to 0.0050 wt%.

S: 0.005 to 0.050 wt%

[0050] S is an element that is present in the steel primarily as sulfide-based inclusions and that is effective for improving the machinability where the steel is used for components shaped by cutting, such as gears. For this effect, at least 0.005 wt% of the element should therefore be added. An excessive addition, however, results in lower fatigue strength. To prevent this, the upper limit must be set to 0.050 wt%.

[0051] Consequently, the S addition is confined to a range of 0.005 to 0.050 wt%.

Pb: 0.01 to 0.09 wt%

[0052] Pb is an element that further improves the machinability as compared with the case of adding S alone. For this effect, at least 0.01 wt% addition of the element is therefore needed. An excessive addition of this element, however, results in lower fatigue strength. At over 0.10 wt%, the handling of Pb is subject to legal restrictions in terms of dust collection equipment, processes, and the like. To prevent this, the upper limit must be set to 0.09 wt%.

[0053] Consequently, the Pb addition is confined to a range of 0.01 to 0.09 wt%.

Bi: 0.04 to 0.20 wt%

[0054] Bi is an element that further improves the machinability as compared with the case of adding S alone. For this effect, at least 0.04 wt% addition of the element is therefore needed. An excessive addition of this element, however, results in lower toughness. To prevent this, the upper limit must be set to 0.20 wt%.

[0055] Consequently, the Bi addition is confined to a range of 0.04 to 0.20 wt%.

Te: 0.002 to 0.050 wt%

[0056] Te is an element that further improves the machinability as compared with the case of adding S alone. For this effect, at least 0.002 wt% of the element should therefore be added. An excessive addition of this element, however, brings about hot brittleness. To prevent this, the upper limit must be set to 0.050 wt%.

[0057] Consequently, the Te addition is confined to a range of 0.002 to 0.050 wt%.

Zr: 0.01 to 0.20 wt%

[0058] Zr is an element that further improves the machinability as compared with the case of adding S alone. For this effect, at least 0.01 wt% of the element should therefore be added. An excessive addition of this element results in lower toughness, however. To prevent this, the upper limit must be set to 0.20 wt%.

[0059] Consequently, the Zr addition is confined to a range of 0.01 to 0.20 wt%.

Ca: 0.0001 to 0.0100 wt%

[0060] Ca is an element that further improves the machinability as compared with the case of adding S alone. For this effect, at least 0.0001 wt% of the element should therefore be added. An excessive addition of this element results in lower toughness, however. To prevent this, the upper limit must be set to 0.0100 wt%.

[0061] Consequently, the Ca addition is confined to a range of 0.0001 to 0.0100 wt%.

[0062] The present invention will now be described in further detail through specific embodiments. Table 2 shows the chemical compositions of inventive steels obtained in actual furnaces on the basis of the above-described data, as well as chemical compositions of comparative steels used for comparison purposes.

Table 2

No.	Chemical Composition (wt%)														
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	Al	Nb	O	N	Ti	B	Ni+ Mo
A	0.21	0.55	0.35	0.008	0.014	0.02	0.75	0.11	0.65	0.023	0.020	0.0009	0.0108	-	-	0.67
B	0.22	0.53	0.35	0.010	0.013	0.15	0.65	0.10	0.15	0.033	0.001	0.0010	0.0051	0.025	0.0020	0.30
I	0.22	0.24	0.65	0.013	0.012	1.59	0.60	0.10	0.18	0.024	-	0.0007	0.0123	-	-	1.77
H	0.21	0.55	0.97	0.012	0.012	0.02	1.04	0.10	0.20	0.024	-	0.0009	0.0121	-	-	0.22

A and B: Inventive Steels

H and I: Comparative Steels

[0063] In the table, Inventive Steel A is a boron-free steel, and Inventive Steel B is a boron-containing steel. In addition, Comparative Steel I is SNCM420H specified in Japanese Industrial Standard (JIS), and Comparative Steel H is a steel based on SCM420H (JIS) and obtained by increasing the Si content.

[0064] These steels were subjected to roller/pitting fatigue tests and carburization impact tests, and the pitting fatigue life and carburization impact strength thereof were evaluated. Fig. 7 is a schematic of the roller/pitting fatigue tester used. In this figure, 1 is a test piece, 2 is a loading roller, 3 and 4 are meshing gears, 5 is a bearing, 6 is a coupling, 7 is a transmission belt, and 8 is a motor. Fig. 8 depicts the shape of the roller/pitting fatigue test piece, and Fig. 9 depicts the shape of the loading roller for the roller/pitting fatigue tester.

[0065] The inventive and comparative steels were first hot-forged to a diameter of 30 mm and were then normalized, yielding five roller/pitting fatigue test pieces such as the one shown in Fig. 8, and five carburization impact test pieces such as the one shown in Fig. 2. These test pieces were subsequently carburized, quenched, and tempered under the conditions shown in Fig. 3.

[0066] The roller/pitting fatigue test pieces were subjected to the roller pitting fatigue test under the conditions shown in Table 3, and their pitting fatigue life was determined. The carburization impact test pieces were subjected to a Charpy impact test, and their carburization impact strength was determined. The results are shown in Table 4. In the roller/pitting fatigue test, 20.00×10^6 rolling cycles were performed, and the test was completed if no pitting had occurred. The results shown in Table 4 are summarized in Fig. 10.

Table 3

Items	Specifics
Maximum Hertzian Stress	2940 MPa
Slip rate	-40%
Rotational speed	1000 r.p.m.
Lubricating oil	Engine oil (Komatsu Genuine Oil EO-30-CD)
Lubricating oil temperature	50°C
Large roller/crowning diameter	300 mmR

Table 4

	Pitting fatigue life ($\times 10^6$)					Carburization impact strength (J/cm^2)				
	n=1	n=2	n=3	n=4	n=5	n=1	n=2	n=3	n=4	n=5
Inventive Steel A	20.00*	20.00*	20.00*	20.00*	20.00*	35.3	36.1	32.8	33.1	37.7
Inventive Steel B	20.00*	20.00*	20.00*	20.00*	20.00*	30.1	34.2	32.2	31.6	34.0
Comparative Steel I	0.75	0.66	0.51	0.47	0.38	35.5	32.1	32.0	33.0	34.8
Comparative Steel H	15.70*	20.00*	13.30	20.00*	20.00*	8.9	15.2	12.2	11.1	7.8

* Tests were completed without any pitting being noted.

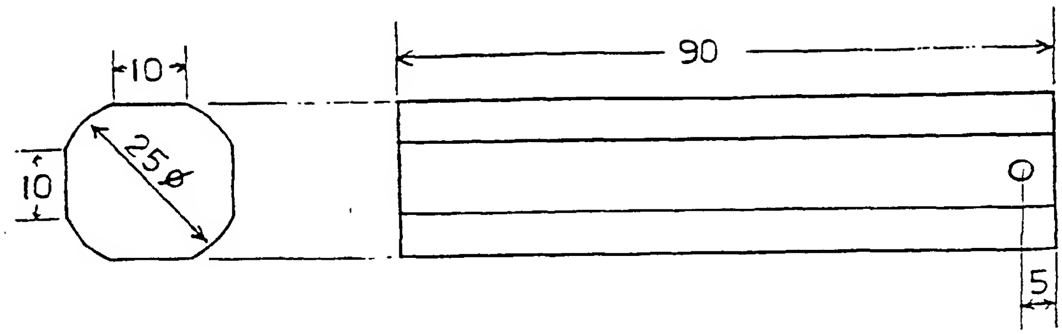
[0067] It can thus be seen that Inventive Steels A and B have a pitting fatigue life of 20.00×10^6 or greater, and a carburization impact strength of 30 J/cm^2 or greater. Comparative Steel I has a carburization impact strength of 30 J/cm^2 or greater but possesses a short pitting fatigue life. In addition, Comparative Steel H has an adequate pitting fatigue life but possesses low carburization impact strength.

[0068] It was thus confirmed that the inventive steel has high pitting fatigue strength and improved impact strength.

[0069] Thus, the present invention allows both pitting fatigue strength and impact strength to be improved merely by adjusting the chemical composition of steel, allowing the stated object to be attained.

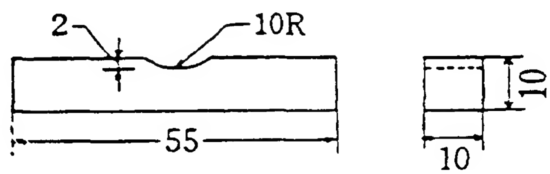
[0070] Consequently, the present invention is effective for reducing the size and weight of carburized gears in current manufacturing processes and in achieving higher outputs with the same sizes and shapes, greatly contributing to reduced costs and improved reliability in gear-related industrial applications.

FIG.1



UNIT:mm

FIG.2



UNIT:mm

FIG.3

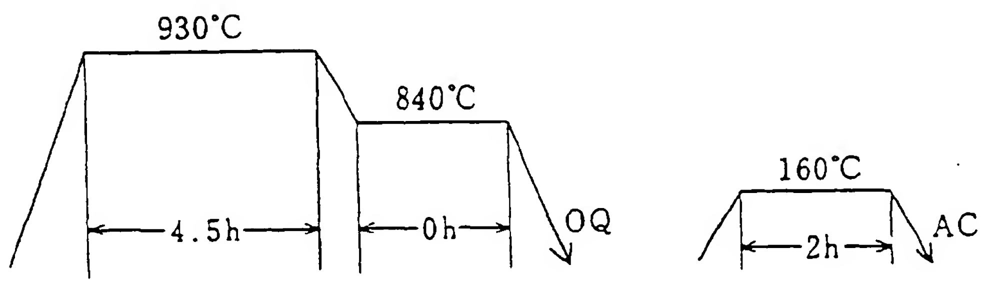


FIG. 4

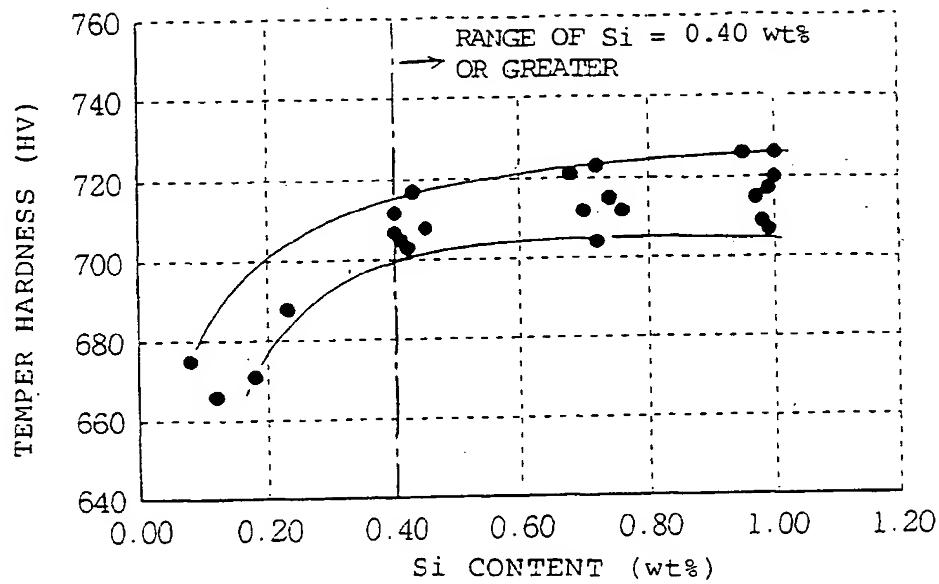

760
740
720
700
680
660
640
TEMPER HARDNESS (HV)
RANGE OF Si = 0.40 wt%
OR GREATER
0.00
0.20
0.40
0.60
0.80
1.00
1.20
Si CONTENT (wt%)

FIG.5

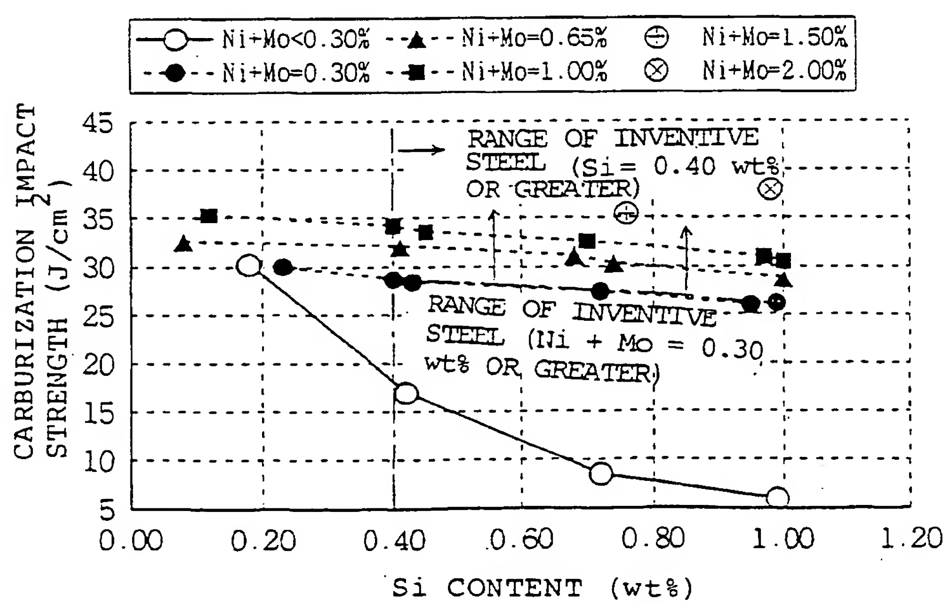

Ni+Mo<0.30%
Ni+Mo=0.65%
Ni+Mo=1.50%
Ni+Mo=0.30%
Ni+Mo=1.00%
Ni+Mo=2.00%
CARBURIZATION IMPACT STRENGTH (J/cm2)
45
40
35
30
25
20
15
10
5
RANGE OF INVENTIVE STEEL (Si = 0.40 wt% OR GREATER)
RANGE OF INVENTIVE STEEL (Ni + Mo = 0.30 wt% OR GREATER)
0.00
0.20
0.40
0.60
0.80
1.00
1.20
Si CONTENT (wt%)

FIG.6

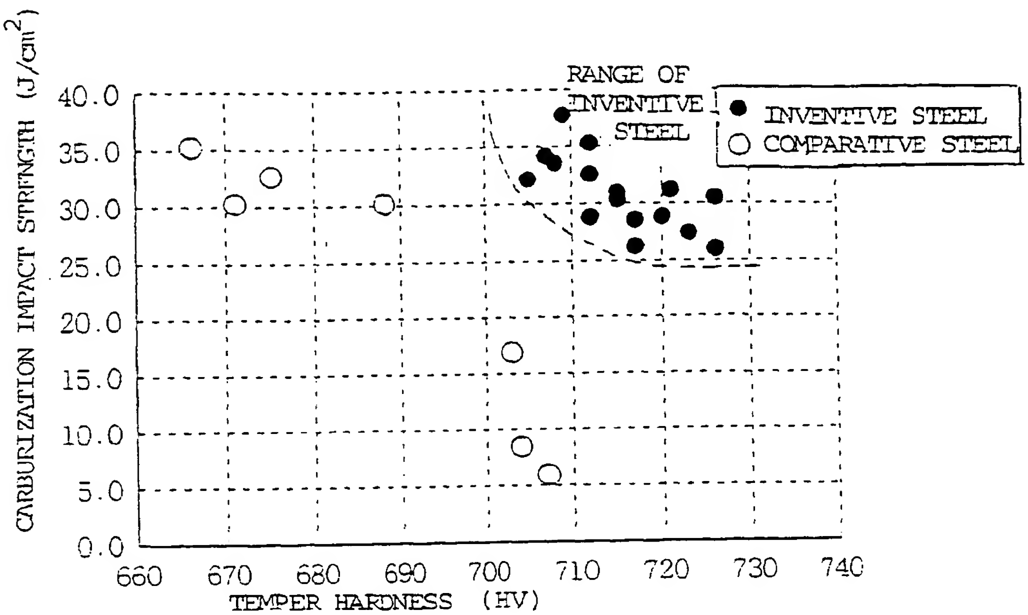

RANGE OF INVENTIVE STEEL
INVENTIVE STEEL
COMPARATIVE STEEL
CARBURIZATION IMPACT STRENGTH (J/cm²)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
660
670
680
690
700
710
720
730
740
TEMPER HARDNESS (HV)

FIG. 7

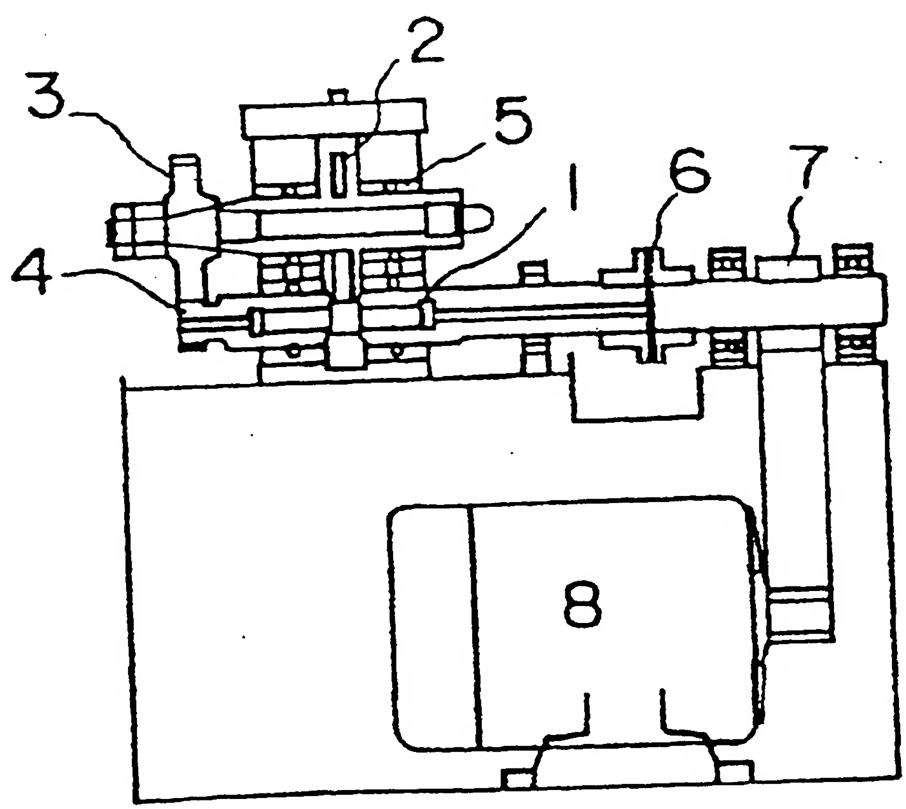
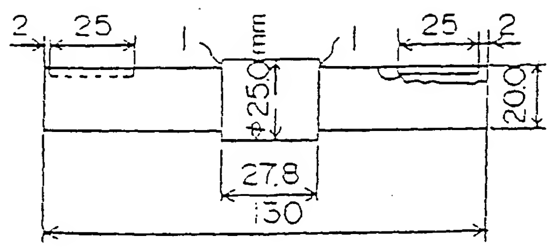
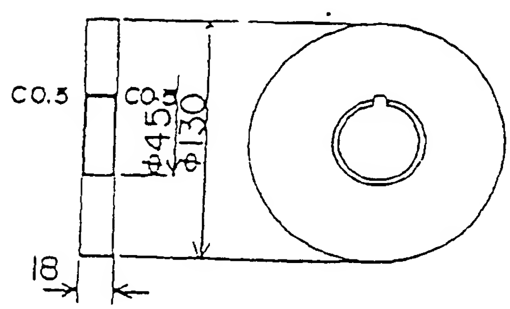

2
3
5
1
6
7
4
8

FIG. 8



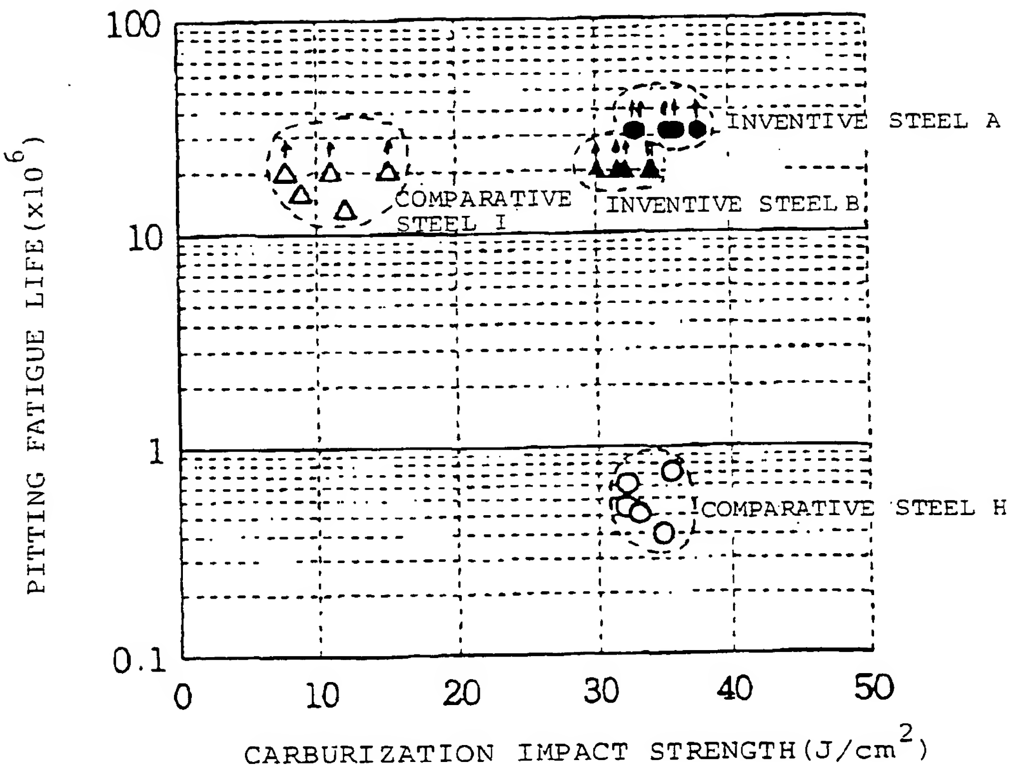
UNIT: mm

FIG. 9



UNIT: mm

FIG.10


100
10
1
0.1
0
10
20
30
40
50
PITTING FATIGUE LIFE(x10^6)
CARBURIZATION IMPACT STRENGTH(J/cm^2)
INVENTIVE STEEL A
INVENTIVE STEEL B
COMPARATIVE STEEL I
COMPARATIVE STEEL H